Probing the QCD Phase diagram Via Net-proton Number Fluctuations at RHIC

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RHIC/AGS Annual User's Meeting

Outline

1. Introduction
2. Experimental results
3. Summary and outlook

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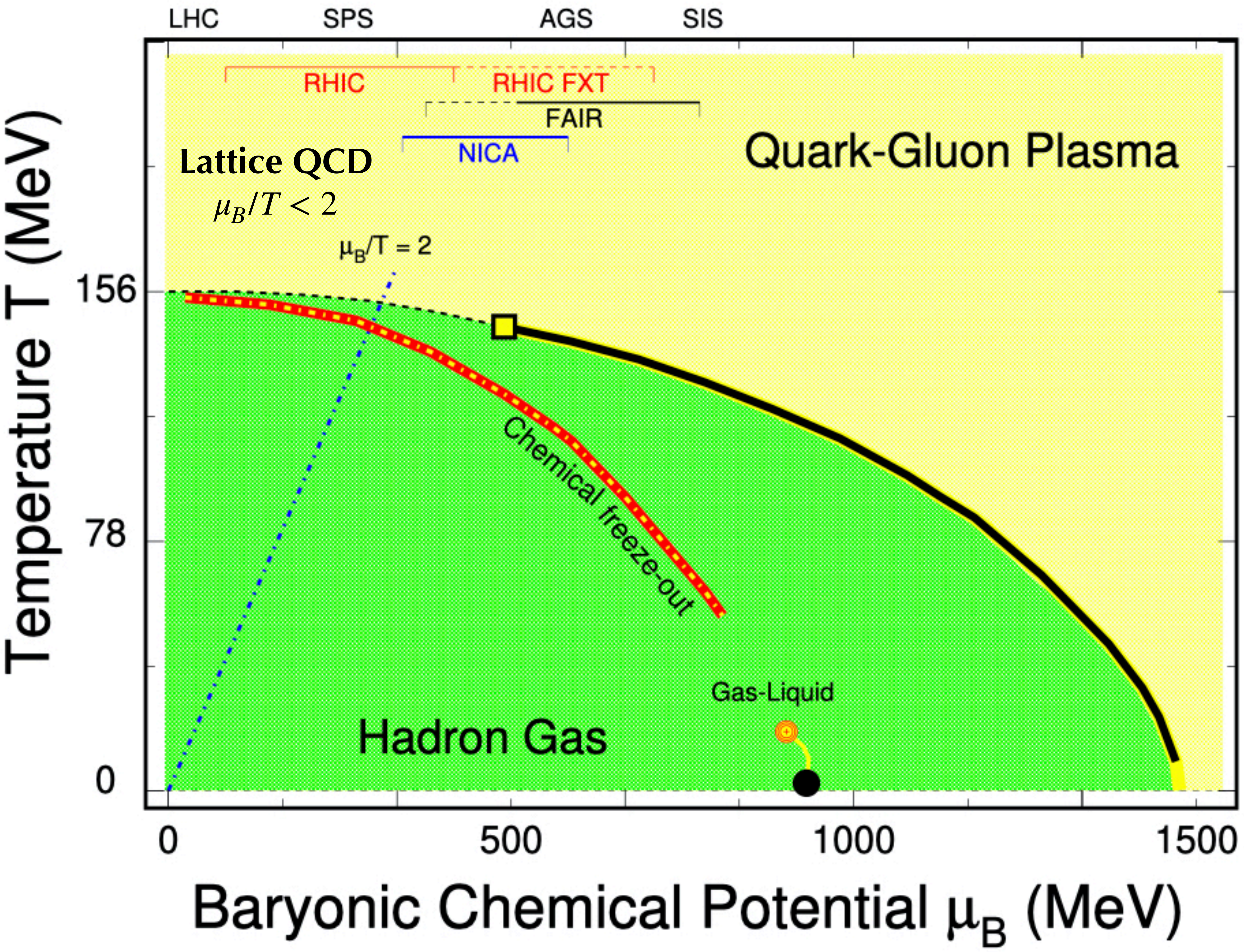
Introduction: QCD Phase Diagram



B. Mohanty, N. Xu, arXiv:2101.09210

Lattice QCD →

Models →

Phase structure:

- QGP and hadronic phase ✓
- Transition temperature (T_c) ✓
- Crossover at small μ_B ($\frac{\mu_B}{T} < 2$) ✓
- 1st order P.T. at large μ_B ?
- **Critical end point** ?

☐ Phase diagram of strongly interacting matter

☐ Largely conjectured

Observables:

- **Cumulants:** $n =$ ***net-proton multiplicity in an event***

$C_1 = < n >$

$C_2 = < \delta n^2 >$ $\quad *\delta n = n - < n >$

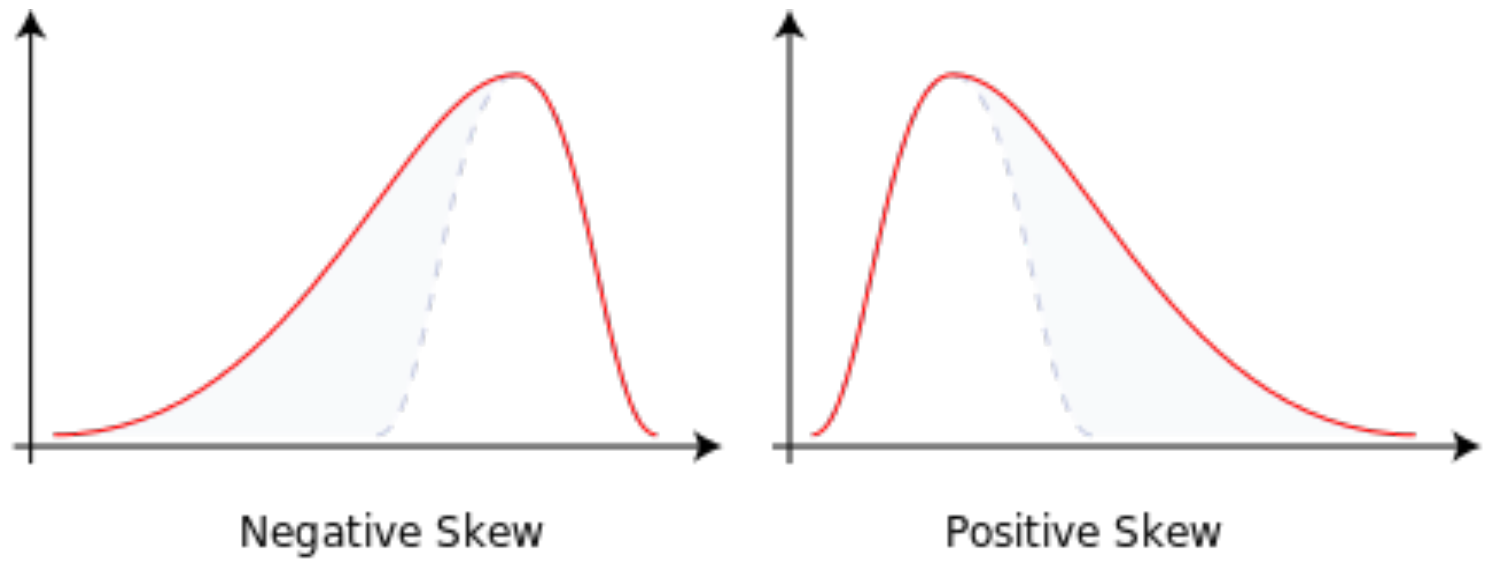
$C_3 = < \delta n^3 >$

$C_4 = < \delta n^4 > - 3 < \delta n^2 >$

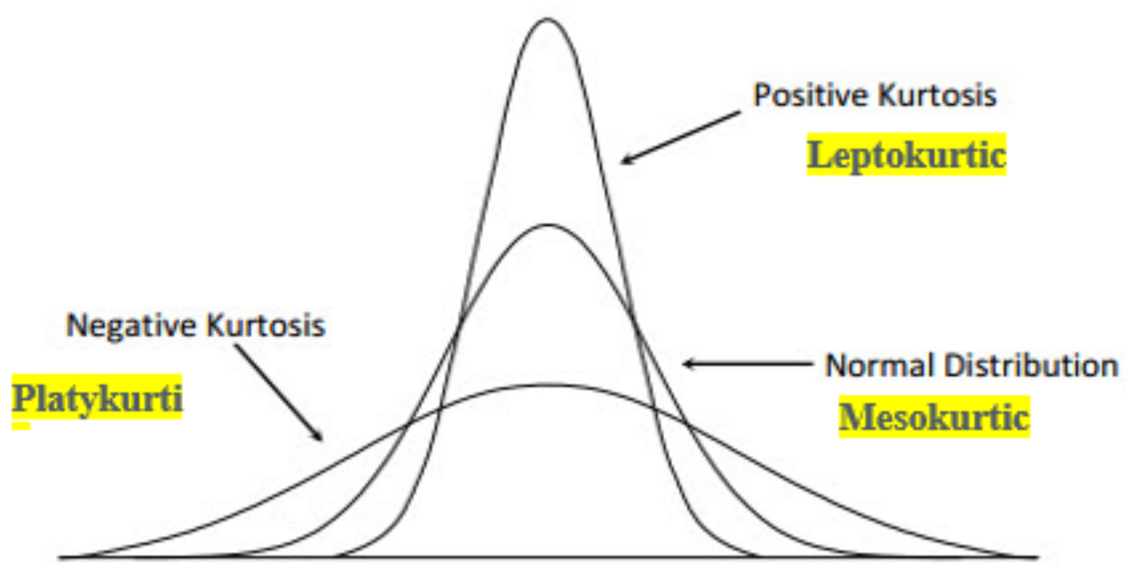
$C_5 = < \delta n^5 > - 10 < \delta n^3 > < \delta n^2 >$

$C_6 = < \delta n^6 > - 15 < \delta n^4 > < \delta n^2 > \; - 10 < \delta n^3 >^2 + 30 < \delta n^2 >^3$

Skewness: Asymmetry



Kurtosis: Peakedness



M. A. Stephanov, PRL 107 (2011) 052301

R.V. Gavai and S. Gupta, PLB696, 459(11)
S. Ejiri, F. Karsch, K. Redlich, PLB633, 275(06)
A. Bazavov et al., PRL109, 192302(12)
S. Borsanyi et al., PRL111, 062005(13)

- **Factorial cumulants:**

$\kappa_1 = C_1$

$\kappa_2 = - C_1 + C_2$

$\kappa_3 = 2C_1 - 3C_2 + C_3$

$\kappa_4 = - 6C_1 + 11C_2 - 6C_3 + C_4$

$\kappa_5 = 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5$

$\kappa_6 = - 120C_1 + 274C_2 - 225C_3 + 85C_4 - 15C_5 + C_6$

Related to correlation length: $C_2 \sim \xi^2, C_4 \sim \xi^7$

Finite size/time effects reduces ξ

Higher order→more sensitivity

Related to susceptibilities: $\frac{C_{4q}}{C_{2q}} = \frac{\chi_4^q}{\chi_2^q}, \frac{C_{6q}}{C_{2q}} = \frac{\chi_6^q}{\chi_2^q}$

Comparison with lattice QCD,
HRG, QCD-based model calculations

Strategy:

Towards making the QCD phase diagram a reality

- ☐ **Perform collisions of nuclei to produce and study QCD matter**
- ☐ Check if produced system is governed by thermodynamics
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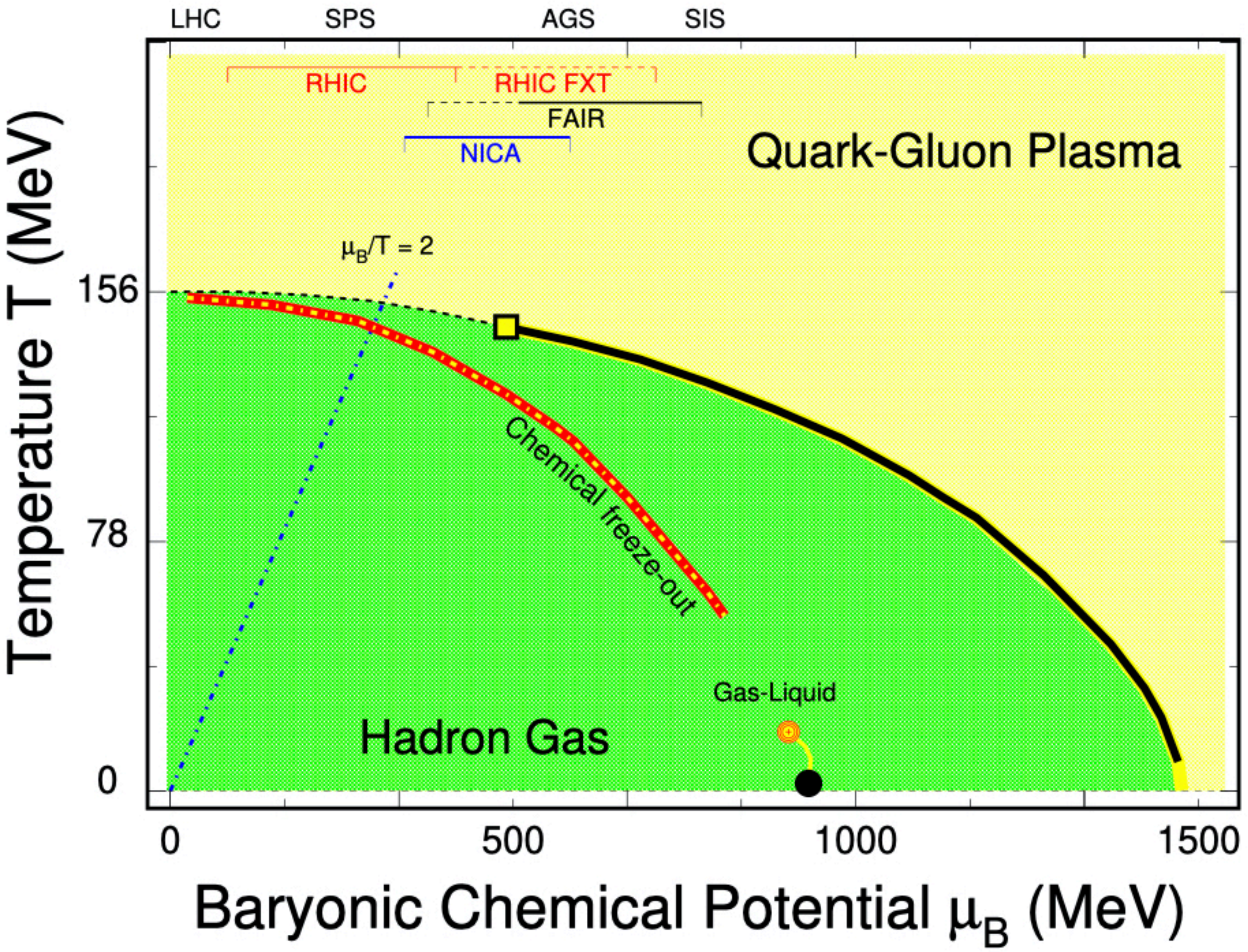
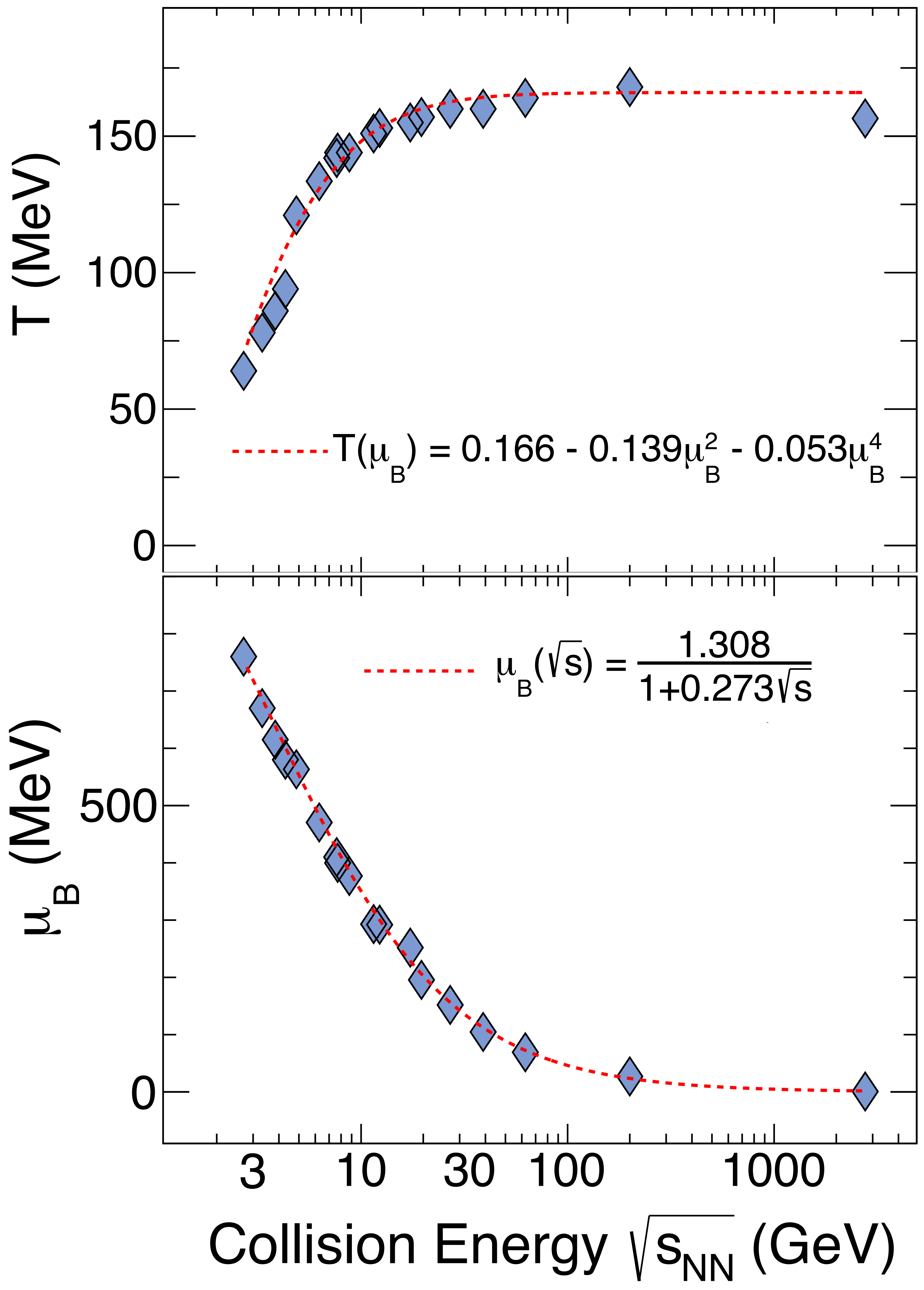
Beam Energy Scan and Study of phase diagram



B. Mohanty, N. Xu, arXiv:2101.09210



P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302

Phase I of BES program (BES-I):

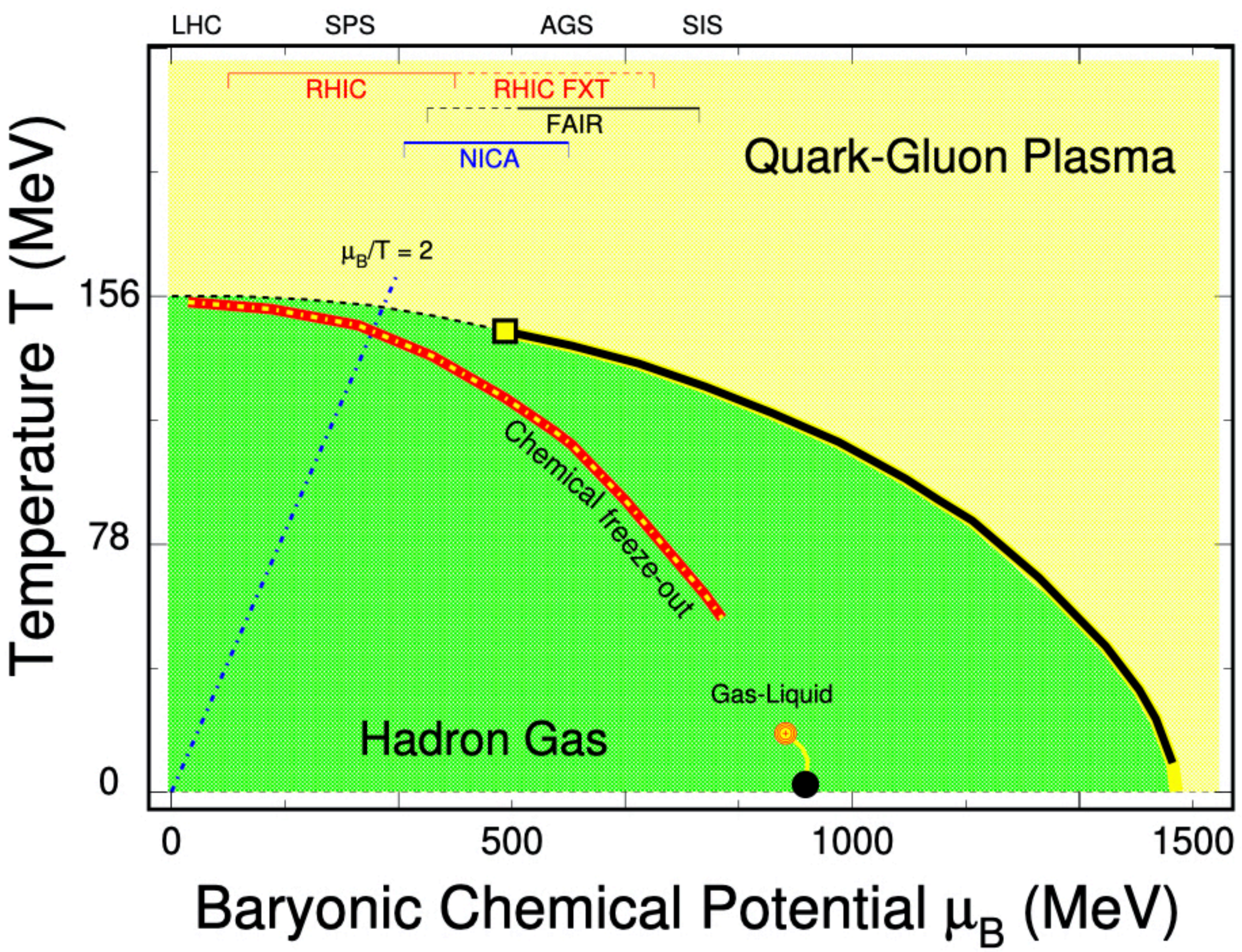
Au+Au collisions

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	μ_B (MeV)
200	220	25
62.4	43	75
54.4	550	85
39	92	112
27	31	156
19.6	14	206
14.5	14	262
11.5	7	316
7.7	2.2	420

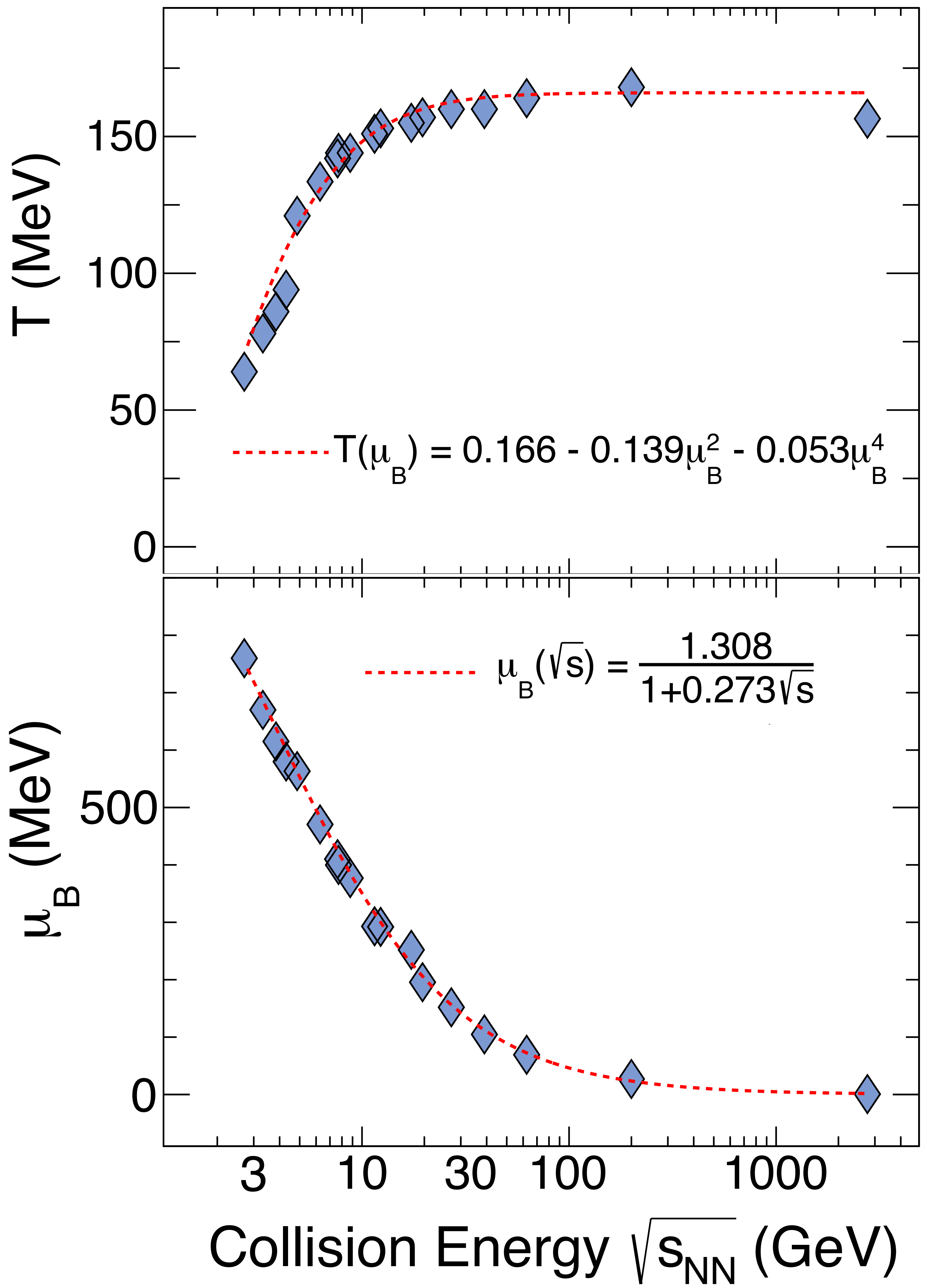
3	140	720

- ☐ Varying collision energy, impact parameter varies T and μ_B of system created
- ☐ Study energy/centrality dependence of cumulants

Beam Energy Scan and Study of phase diagram



B. Mohanty, N. Xu, arXiv:2101.09210



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3 GeV results are analyzed by Sam Heppelman and Yu Zhang (CCNU)

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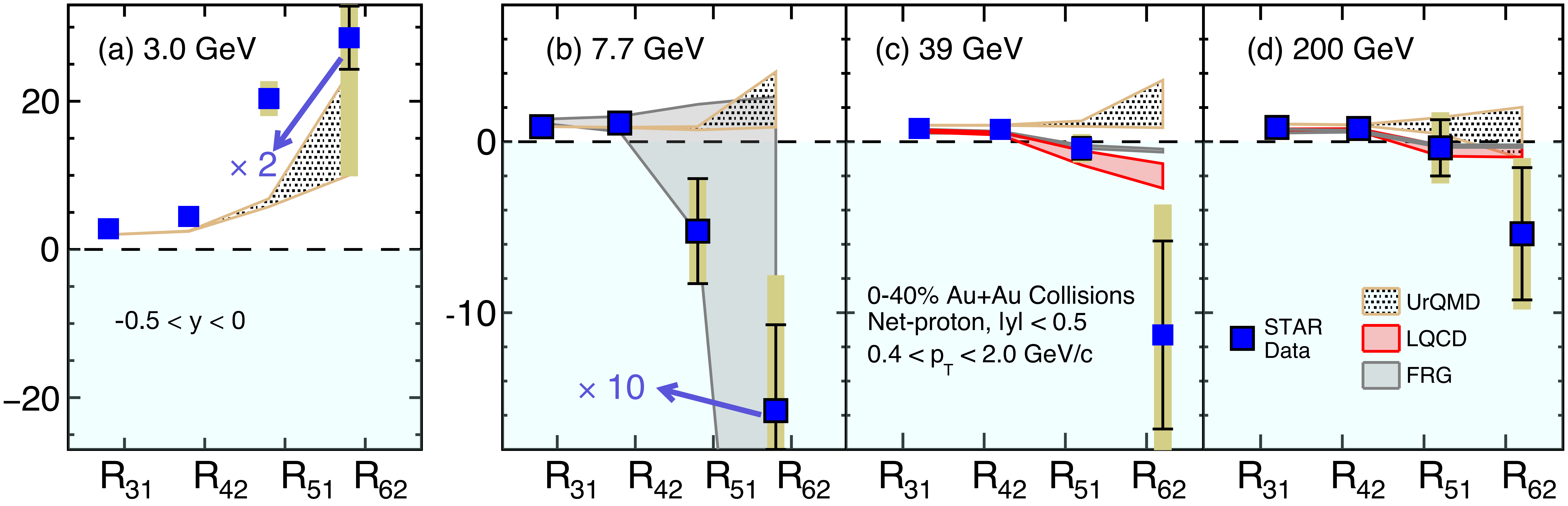
Results: Study Of Thermodynamics

Study of thermodynamics: Net-baryon $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$ - Lattice



$R_{31} = C_3/C_1$ $R_{42} = C_4/C_2$ $R_{51} = C_5/C_1$ $R_{62} = C_6/C_2$

- ☐ Within uncertainties, 7.7 - 200 GeV data consistent with lattice predicted hierarchy.
- ☐ At 3 GeV, violation of ordering is seen. Observed ordering reproduced by UrQMD.

LQCD: HotQCD, PRD101,074502 (2020)
FRG: Wei-jie Fu et. al, PRD 104, 094047 (2021)
STAR: PRL 130, 082301 (2023)
: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
: PRC 104, 024902 (2021)

Strategy:

Towards making the QCD phase diagram a reality

- ☐ Perform collisions of nuclei to produce and study QCD matter
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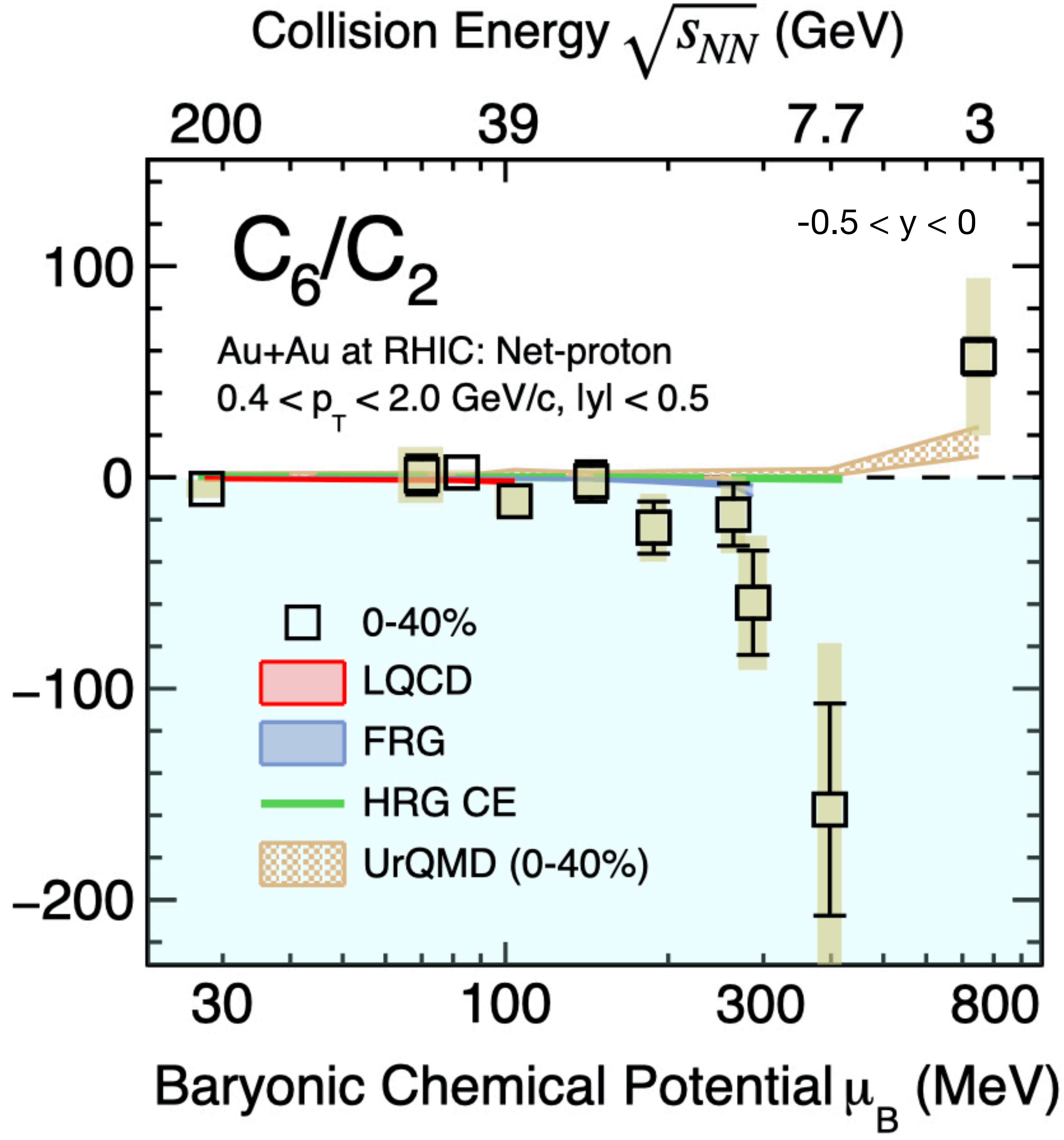
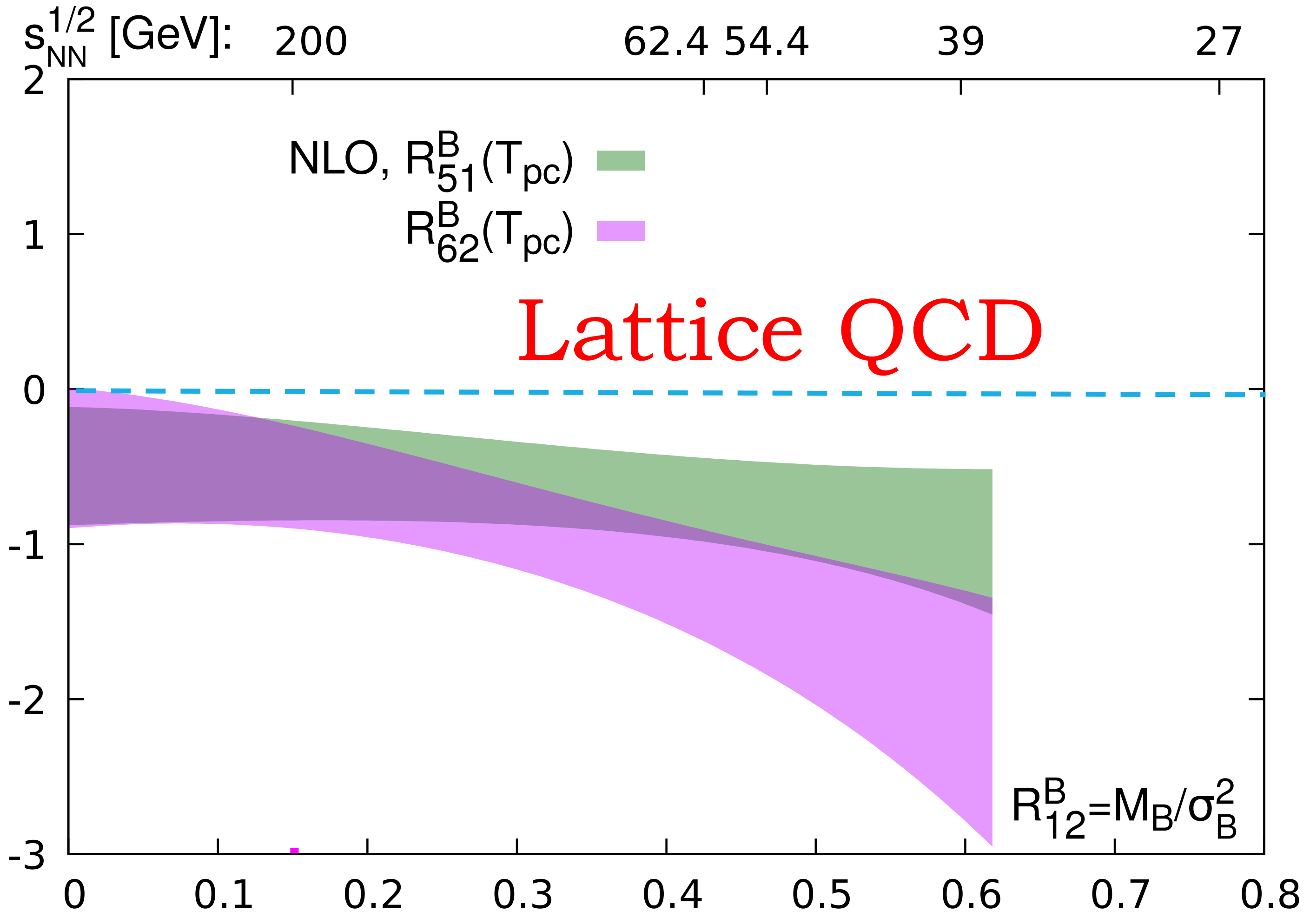
Results: Studying the Crossover





- Increasingly negative C_6/C_2 (down to 7.7 GeV) with decreasing $\sqrt{s_{NN}}$ (1.7σ significance) - a trend consistent with lattice QCD

- $C_6/C_2 > 0$ at 3 GeV, sign reproduced by UrQMD.

STAR: PRL 127, 262301 (2021)
STAR: PRL 130, 082301 (2023)
HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
LQCD: HotQCD, PRD 101, 074502 (2020)
FRG: Wei-jie Fu et. al, PRD 104, 094047 (2021)

Strategy:

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- ☐ Perform collisions of nuclei to produce and study QCD matter
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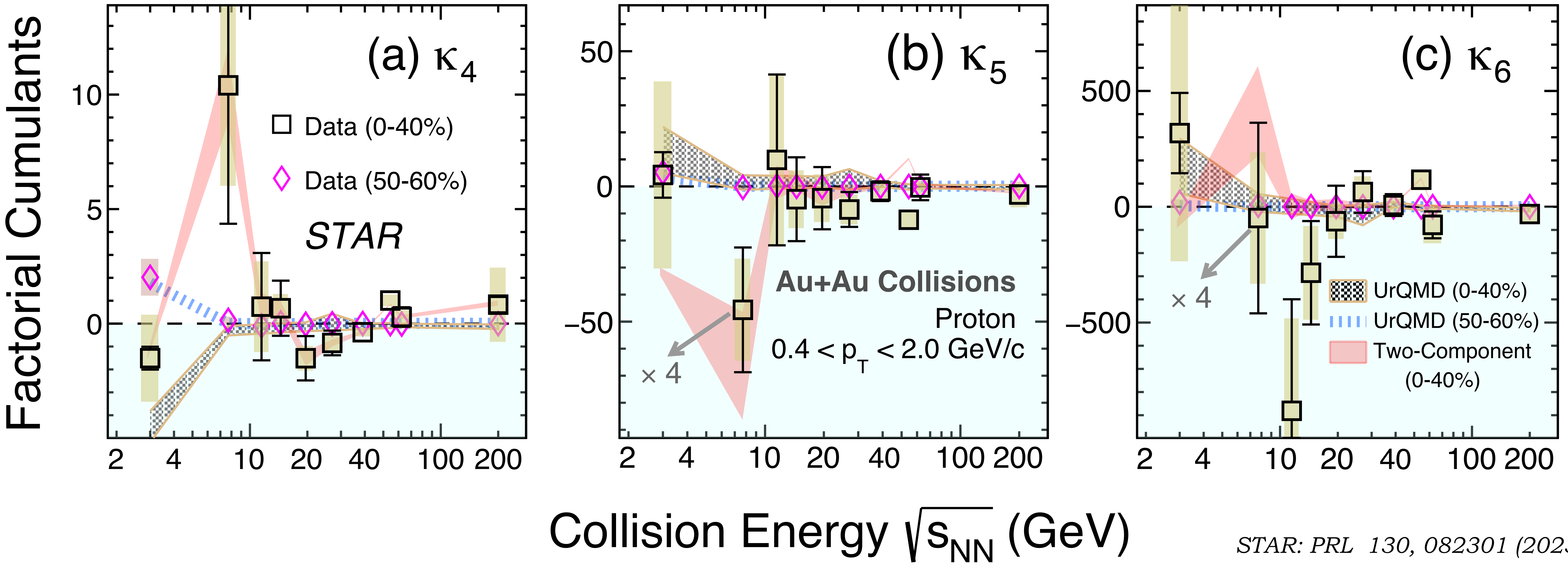
- ☐ **Search for signatures of 1st order P.T. at large** μ_B
- ☐ Search for signatures of QCD critical point

Results: Studying the First-order Phase Transition

Two-component distribution: Large factorial cumulants with alternating sign



STAR: PRL 130, 082301 (2023)

- For $\sqrt{s_{NN}} \geq 11.5$ GeV, the proton κ_n within uncertainties does not support the two-component shape of proton distributions expected near a 1st order P.T.

- Precision measurement needed.

Strategy:

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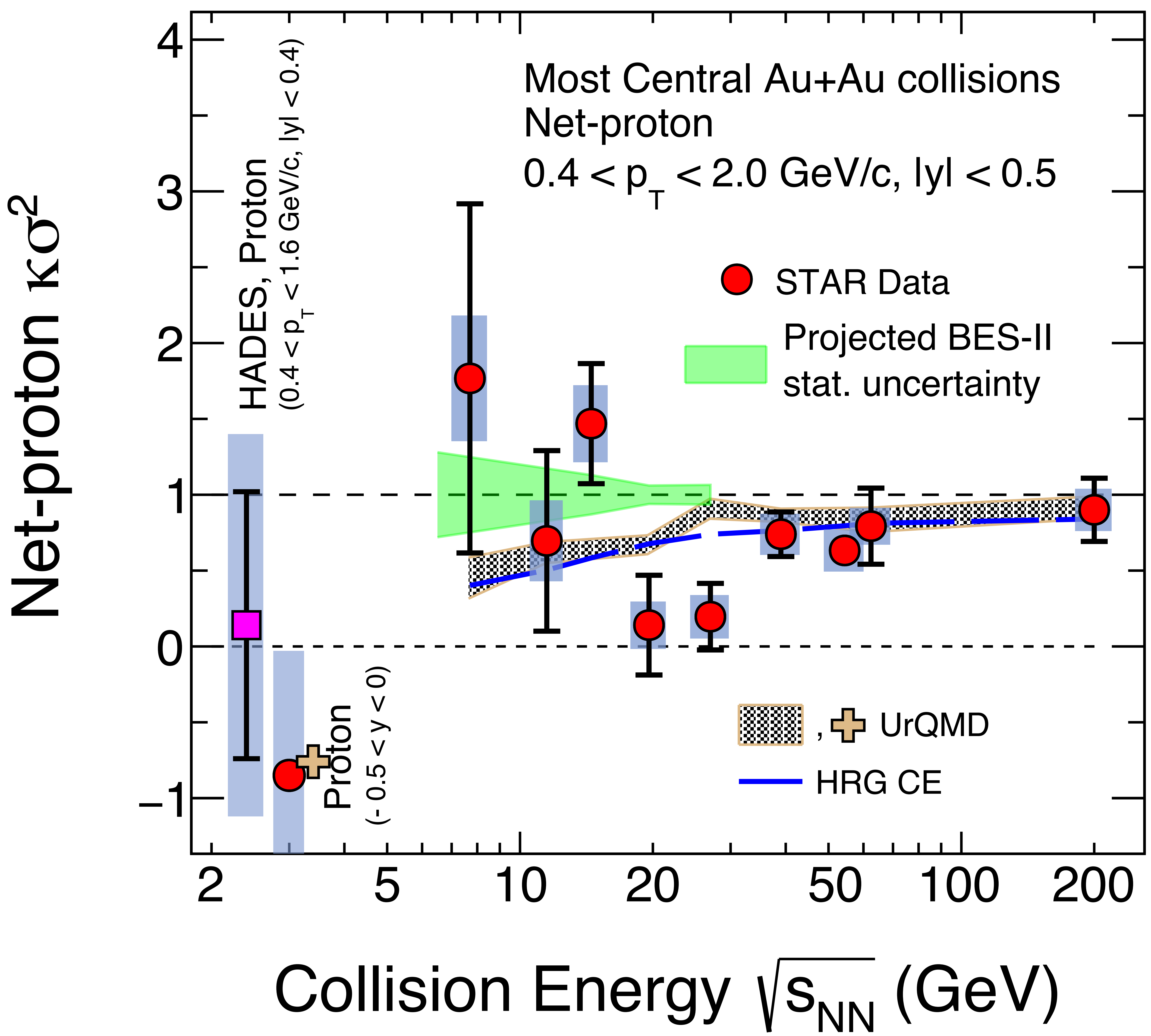
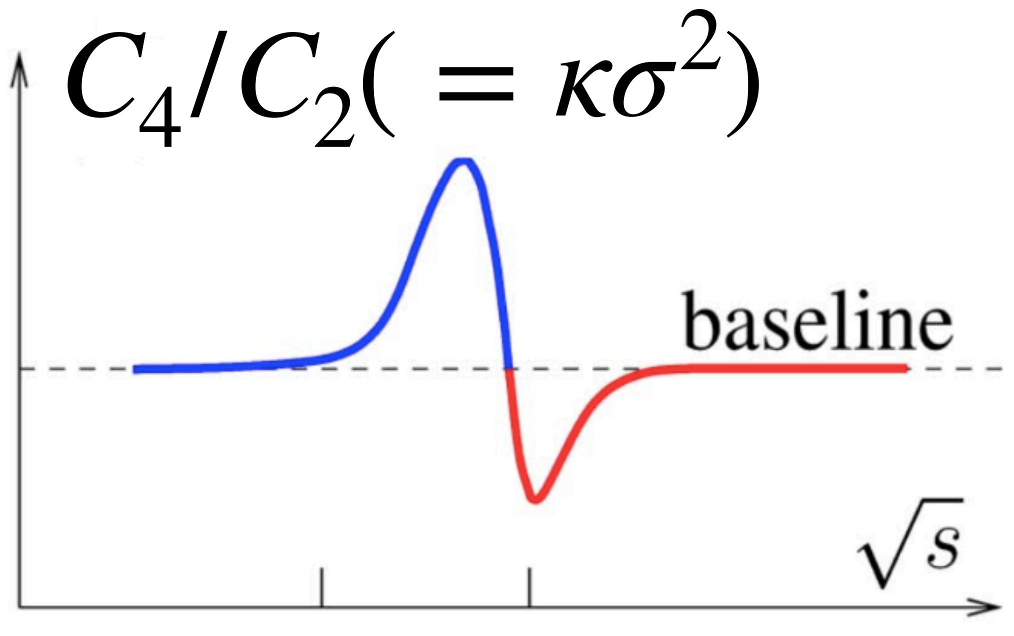
- ☐ Search for signatures of 1st order P.T. at large μ_B
- ☐ **Search for signatures of QCD critical point**

Results: Search for the Critical Point



HADES: PRC 102, 024914 (2020)
STAR: PRL 127, 262301 (2021)
STAR: PRL 128, 202302 (2022)
HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)



M. A. Stephanov, PRL 107 (2011) 052301

- ☐ Non-monotonic collision energy dependence observed for net-proton C_4/C_2 at ~3σ level
  – consistent with CP expectation.
  Non-CP models fail to reproduce the trend.
- ☐ Suppression observed at $\sqrt{s_{NN}} = 3\mathrm{GeV}$ ($\mu_B =$ 750 MeV), consistent with hadronic baseline
- ☐ Precision measurement from BES-II ongoing

Findings:

- ☐ Perform collisions of nuclei to produce and study QCD matter
- ☐ Check if produced system is governed by thermodynamics

  Data ($\sqrt{s_{NN}} \geq 7.7$ GeV or $\mu_B < 420$ MeV) within uncertainties favors ordering expected from lattice thermodynamics. 3 GeV data violates. QCD matter out of equilibrium at 3 GeV?

- ☐ Experimentally establish crossover at small μ_B

  Observed sign and trend in data ($\sqrt{s_{NN}} \geq 7.7$ GeV) consistent with calculations from lattice QCD ($\mu_B < 110$ MeV) with a crossover at $O(\sim 1\sigma)$ significance level.

- ☐ Search for signs of 1st order P.T. at large μ_B

  Data ($\sqrt{s_{NN}} > 7.7$ GeV) within uncertainties suggest absence of any bimodal structure expected near 1st order phase transition.

- ☐ Search for signs of QCD critical point

  Hint of on-monotonic energy dependence observed in data around ($\sqrt{s_{NN}} = 7.7$ - 27 GeV) within $\lesssim 3\sigma$ level, consistent with model expectation with a CP.

Taken collectively:

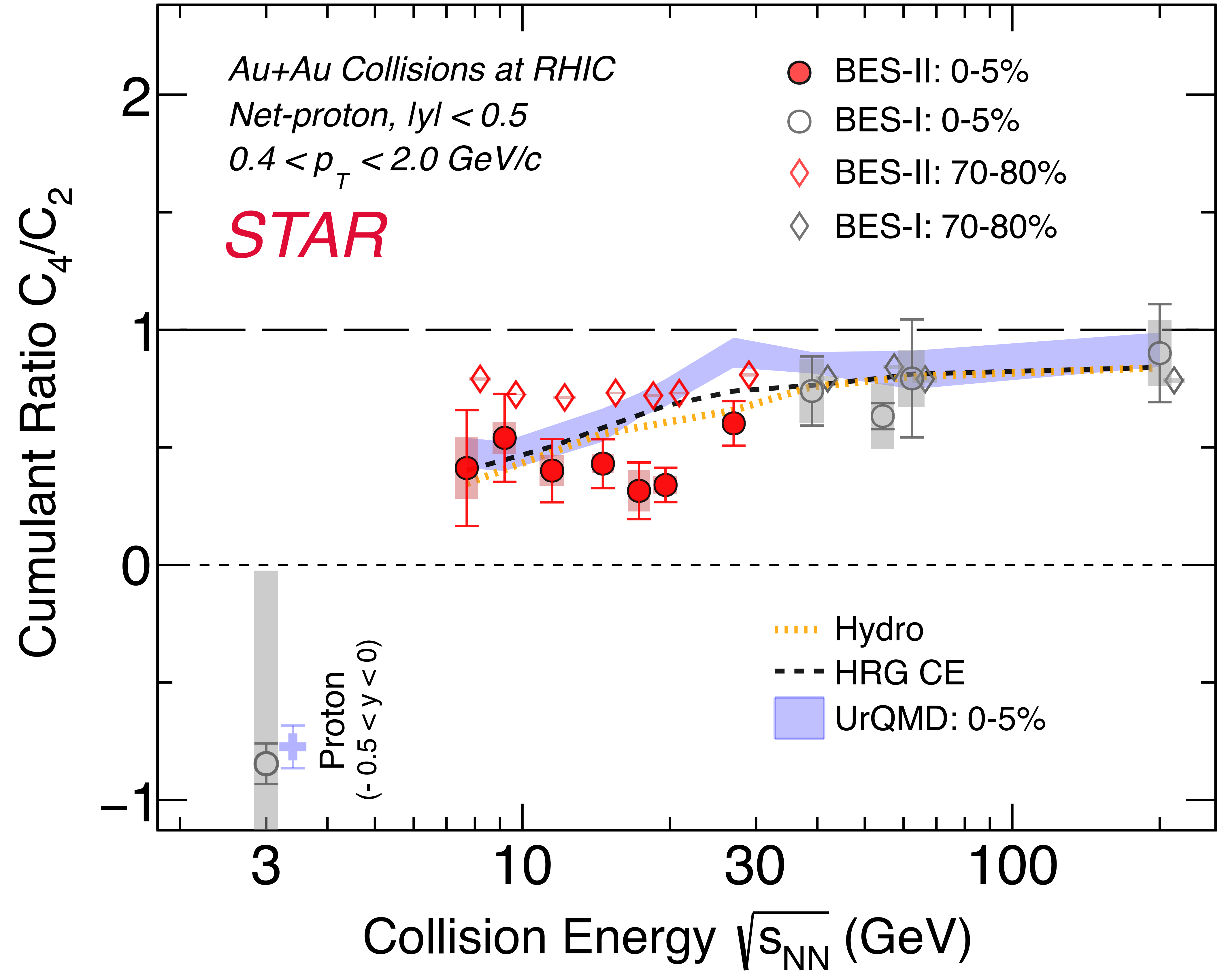
- QCD phase structure starkly different between low $\mu_B \sim 20$ MeV ($\sqrt{s_{NN}} = 200$ GeV) and high $\mu_B \sim 720$ MeV ($\sqrt{s_{NN}} = 3$ GeV)

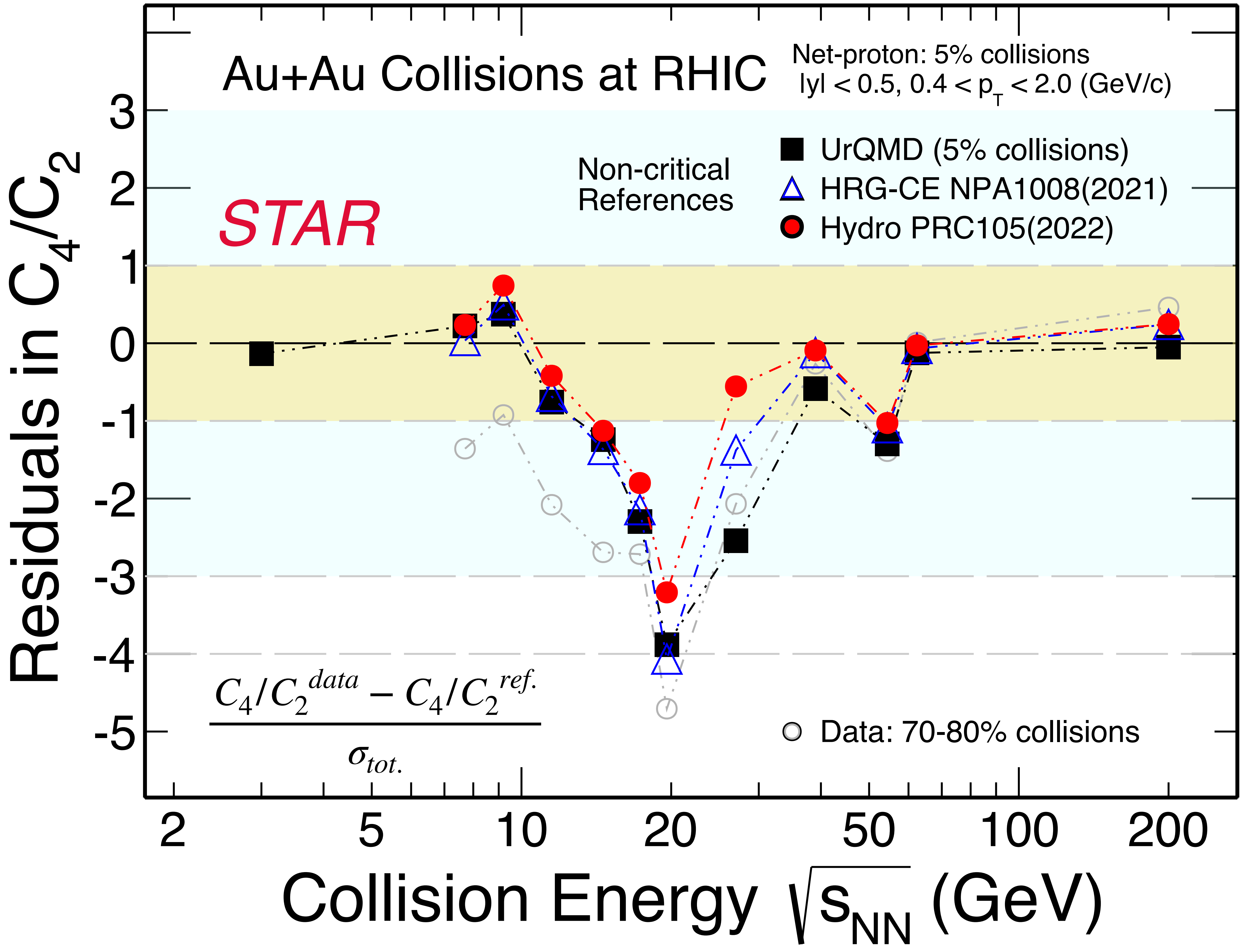
- CP (if it exists) could be within $\sqrt{s_{NN}} = 3$ - 27 GeV

Analysis Outlook: Precision Data From BES-II

- Interesting trends seen in BES-I data. Need for precision measurements for confirmation.
- **BES-II at RHIC: ~10-20 fold increase in statistics and several important detector upgrades and a new fixed target program. Precision measurement from BES-II ongoing!**

BES-II data: $\sqrt{s_{NN}} = 7.7$ - 27 GeV (collider runs) have been released





More results to come. **Exciting times ahead!**

Yige Huang: talk, wednesday
Bappa Mondal: Poster

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)

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***PhD avisor*
**postdocs*

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